

The distribution of SNRs with Galactocentric radius

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Abstract. In order to determine the Galactic distribution of supernova remnants (SNRs) there are two main difficulties: (i) there are selection effects which mean that catalogues of SNRs are not complete, and (ii) distances are not available for most SNRs, so distance estimates from the ‘ $\Sigma-D$ ’ relation are used. Here I compare the observed distribution of 69 ‘bright’ SNRs with Galactic longitude with that expected from the projection of various model Galactocentric radius distributions. This does not require distances from the ‘ $\Sigma-D$ ’ relation, and selecting only ‘bright’ remnants aims to avoid major issues with the selection effects. Although this method does not provide a direct inversion to the 3-D distribution of SNRs in the Galaxy, it does provide useful constraints on the Galactocentric radius distribution. For a combined power-law/exponential model for SNR surface density variation with Galactocentric radius, the best fitted distributions are more concentrated towards lower radii than the distribution derived by Case & Bhattacharya [1].

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INTRODUCTION

Supernova remnants (SNRs) are important sources of energy and high energy particles in the Galaxy. Consequently the distribution of SNRs with Galactocentric radius is of interest for studies of cosmic rays in the Galaxy, and the high energy γ -rays they produce from interaction with the interstellar medium (see, for example, Ackermann et al. [2] and Vladimirov et al. [3]). Here I discuss some of the problems in constructing the Galactic distribution of SNRs, particularly due to selection effects, and the fact that distances are not available for most SNRs. I then compare the observed distribution of SNRs with Galactic longitude with the expected distribution from various (simple) models, in order to provide constraints on the Galactic distribution of SNRs.

BACKGROUND

Currently there are 274 catalogued Galactic SNRs Green [4]¹. In order to obtain the Galactic distribution of SNRs from their observed Galactic coordinates there are two major hurdles that have to be overcome: (i) distances are not available for all SNRs, and (ii) there are significant observational selection effects which means that the catalogue of SNRs is incomplete.

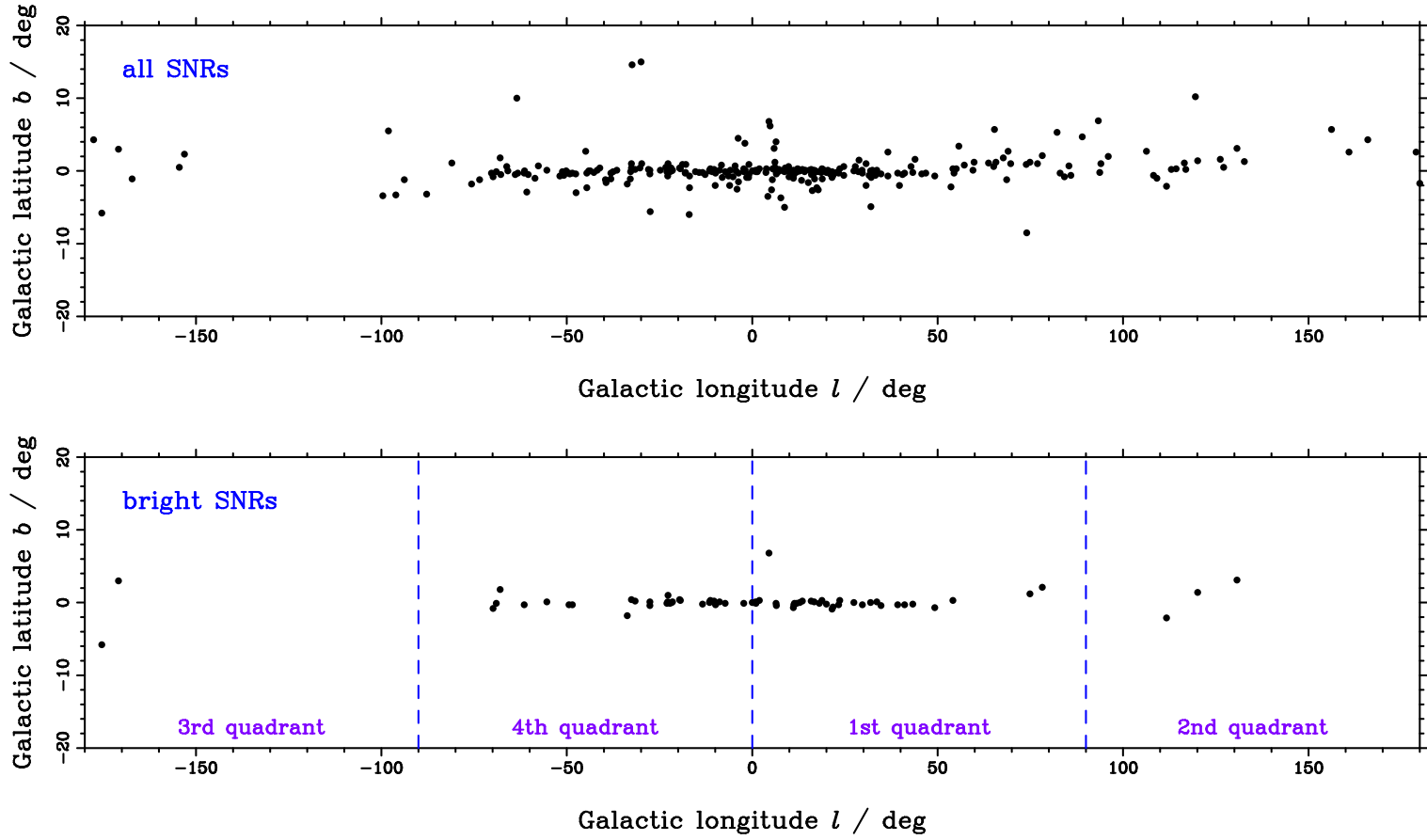
¹ See also: <http://www.mrao.cam.ac.uk/surveys/snr/>

Selection effects

Although some SNRs have first been identified at optical or X-ray wavelengths, the vast majority have been identified from radio observations, and it is radio observations – which are not affected by absorption – which define the effective completeness of current SNR catalogues. Basically the selection effects that apply are (e.g. Green [5]): (i) surface-brightness (Σ), and (ii) angular size.

For a SNR to be identified it needs to be bright enough to be distinguished from the Galactic background. For much of the Galactic plane, the deepest, large scale survey is that made at 2.7-GHz with the Effelsberg 100-m telescope (Reich et al. [6], Fürst et al. [7]), which identified many new SNRs (Reich et al. [8]). In the region covered by this survey – i.e. $358^\circ < l < 240^\circ$, $|b| < 5^\circ$ – additional new SNRs have subsequently been identified, from a variety of other observations. Most of these newly identified remnants are relatively faint. Of the 60 SNRs that have been identified from observations made since the Effelsberg 2.7-GHz survey, 54 are below a surface brightness of $10^{-20} \text{ W m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$ at 1 GHz. I take this surface brightness to be the approximate, single effective Σ -limit of the Effelsberg surveys, and hence of the current Galactic SNR catalogue overall. (Note that the number of catalogued remnants with a surface above this limit are 35 and 29 in the 1st and 4th Galactic quadrants respectively, which are consistent within Poisson errors.) In practice, however, it is not easy to identify SNRs close to this limit in regions of the Galactic plane with high and complex background radio emission, i.e. close to the Galactic Centre. (The other 6 sources are at most only a factor of about 3 brighter than this nominal limit, are close to the Galactic Centre, or are < 10 arcmin in extent, so that the second selection effect – discussed below – also applies.) Figure 1 shows the observed distribution in Galactic coordinates of both (a) all known SNRs, and (b) the 69 SNRs brighter than the nominal surface brightness completeness limit of $10^{-20} \text{ W m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$ at 1 GHz. Taking this surface brightness limit shows a distribution more closely correlated towards both $b = 0^\circ$ and the Galactic Centre. This is not surprising, as the lower radio emission from the Galaxy in the 2nd and 3rd quadrants, and away from $b = 0^\circ$, means it is easier to identify faint SNRs in these regions.

An additional selection effect is that it is generally necessary to resolve a SNR in order to recognise its structure. Although some limited portions of the Galactic plane have been observed with high resolutions, available large area surveys have limited resolution. For example, the Effelsberg surveys noted above have a resolution of 4.3 arcmin, making it difficult to recognise the structure of a remnant unless it is ~ 10 arcmin or larger in extent. This means that there is a deficit of small angular size, i.e. young but distant SNRs (see further discussion in Green [9]), but this selection effect is not easy to quantify. Also, most missing young remnants will be on the far side of the Galaxy, and appear near $b = 0^\circ$ and also near $l = 0^\circ$, which is where the Galactic background is brightest, and where there is more likely to be confusion with other Galactic sources along the line of sight.



1: Galactic distribution of: (top) all 274 catalogued SNRs, and (bottom) the brighter 69 remnants, with surface brightnesses above $10^{-20} \text{ W m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$ at 1 GHz.

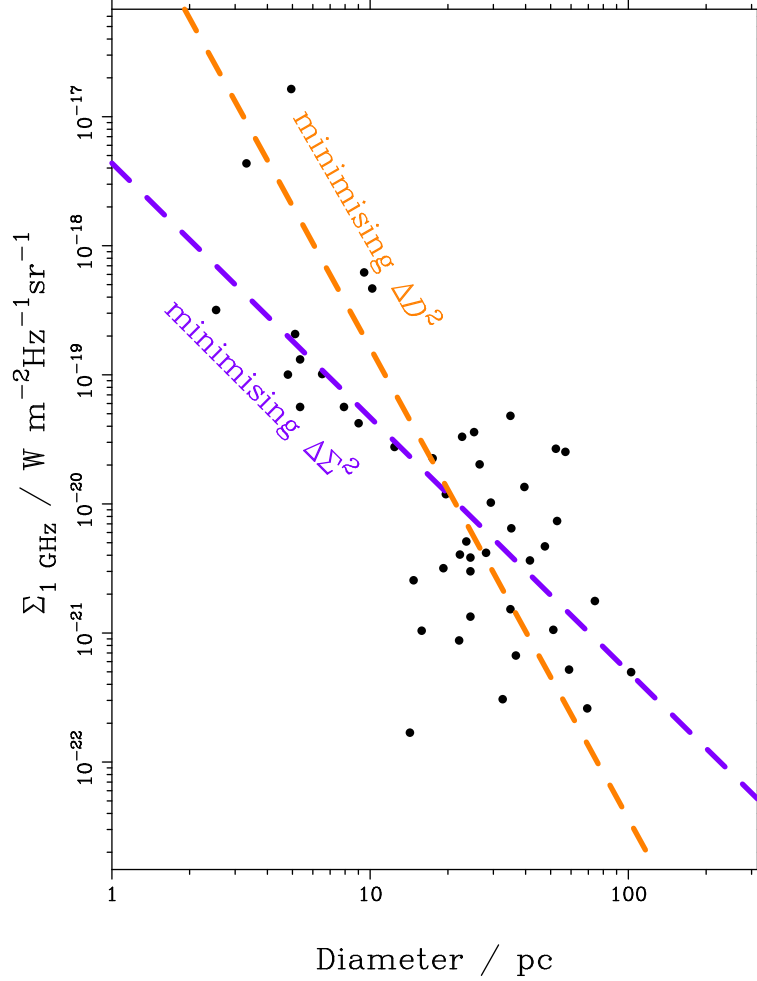


FIGURE 2. The ‘ $\Sigma-D$ ’ – i.e. $\log(\text{surface brightness}, \Sigma)$ versus $\log(\text{diameter}, D)$ – for 47 Galactic SNRs for which distance determinations are available. Also plotted are the least square straight line regressions if the square deviations in Σ or else in D are minimised.

The ‘ $\Sigma-D$ ’ relation

In order to directly construct the Galactic distribution of SNRs it is necessary to know the distance to each catalogued remnant. However, distances measurements are only available for about 20% of currently known SNRs. Often the statistical correlation between the *observed* surface brightness (Σ) and diameter, D , has been used to derive diameters – and hence distances, $d = D/\theta$, using the *observed* angular size – for SNRs for which distance determinations are not available. This is using the ‘ $\Sigma-D$ ’ relation, usually parameterised as

$$\Sigma = CD^{-n}$$

since, for remnants with known distances, physically small ones tend to have larger surface brightnesses than larger remnants. (Note that, as discussed in Green [9], much

of this correlation is arguably due to a D^{-2} bias.) In practice, however, SNRs show a wide range of physical diameters for a given surface brightness, and so the ‘ $\Sigma-D$ ’ relation is of limited use for determining distances to individual remnants (e.g. Green [5, 9]). And because of the selection effects noted above, the full range of properties of SNRs may be even larger than is evident currently, since faint, small angular size (i.e. likely physically small also) remnants are difficult to identify.

Moreover, as noted by Green [9], some use of the ‘ $\Sigma-D$ ’ relation for statistical studies has been affected by using inappropriate straight line regressions. If the $\Sigma-D$ relation is to be used to predict D -values from observed Σ -values, then a least square regression that minimises the square deviations in D should be used, not one that minimises the square deviations in Σ . Given there is a quite a large scatter in the $\Sigma-D$ plane for SNRs with known distances, the differences between these regressions are significant (e.g. see Isobe et al. [10]), particularly for the fainter or brighter remnants. For example, Case & Bhattacharya [1] minimised the square deviations on Σ , and obtained a $\Sigma-D$ relation with $n = 2.64 \pm 0.26$ (for 37 ‘shell’ remnants, including Cas A), which they commented was a considerably flatter $\Sigma-D$ slope than had been obtained previously (e.g. Milne [11] derived $n = 3.8$, Lozinskaya [12] derived $n = 3.45$). However, by minimising square deviations in D , for the calibrators used by [1], $n = 3.53 \pm 0.33$ is obtained, which is a much steeper $\Sigma-D$ slope, and is consistent with previously derived slopes. This is illustrated in Figure 2, for a sample of SNRs with known distances (these are not the same sample as used by Case & Bhattacharya [1], but show the main feature, the difference in fitted slopes for different regressions). Case & Bhattacharya [1] went on to derive the Galactic distribution of SNRs, using their $\Sigma-D$ slope, which is not steep enough, and hence *overestimates* the diameters – and distances – for the majority of SNRs, which are relatively faint.

THE GALACTIC DISTRIBUTION OF SNRS

Rather than attempting to derive the 3-D distribution of Galactic SNRs from their observed properties, which would require reliable distances – and corrections for selection effects if all known SNRs were to be used – I follow the method used in Green [13, 14]. This simply compares the observed distribution of SNRs in Galactic longitude, l , using only brighter remnants above the nominal surface-brightness limit of current catalogues, with the expected distribution projected from various models.

In Green [13, 14] a simple Gaussian model for the surface density of SNRs in the Galactic disk was used, which peaks at the Galactic Centre. However, the observed radial distributions of other star formation tracers (e.g. pulsars and star formation regions, see Bronfman et al. [15], Lorimer et al. [16]) indicate a minimum at the Galactic Centre, and so here I use a two parameter mixed power-law/exponential radial distribution for the density of SNRs with Galactocentric radius, R , i.e.

$$\propto \left(\frac{R}{R_{\odot}} \right)^A \exp \left[-B \frac{(R - R_{\odot})}{R_{\odot}} \right]$$

with $R_{\odot} = 8.5$ kpc, the distance to the Galactic Centre. Figure 3 shows the observed distribution of SNRs with $\Sigma > 10^{-20} \text{ W m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$ from Green [4], together with

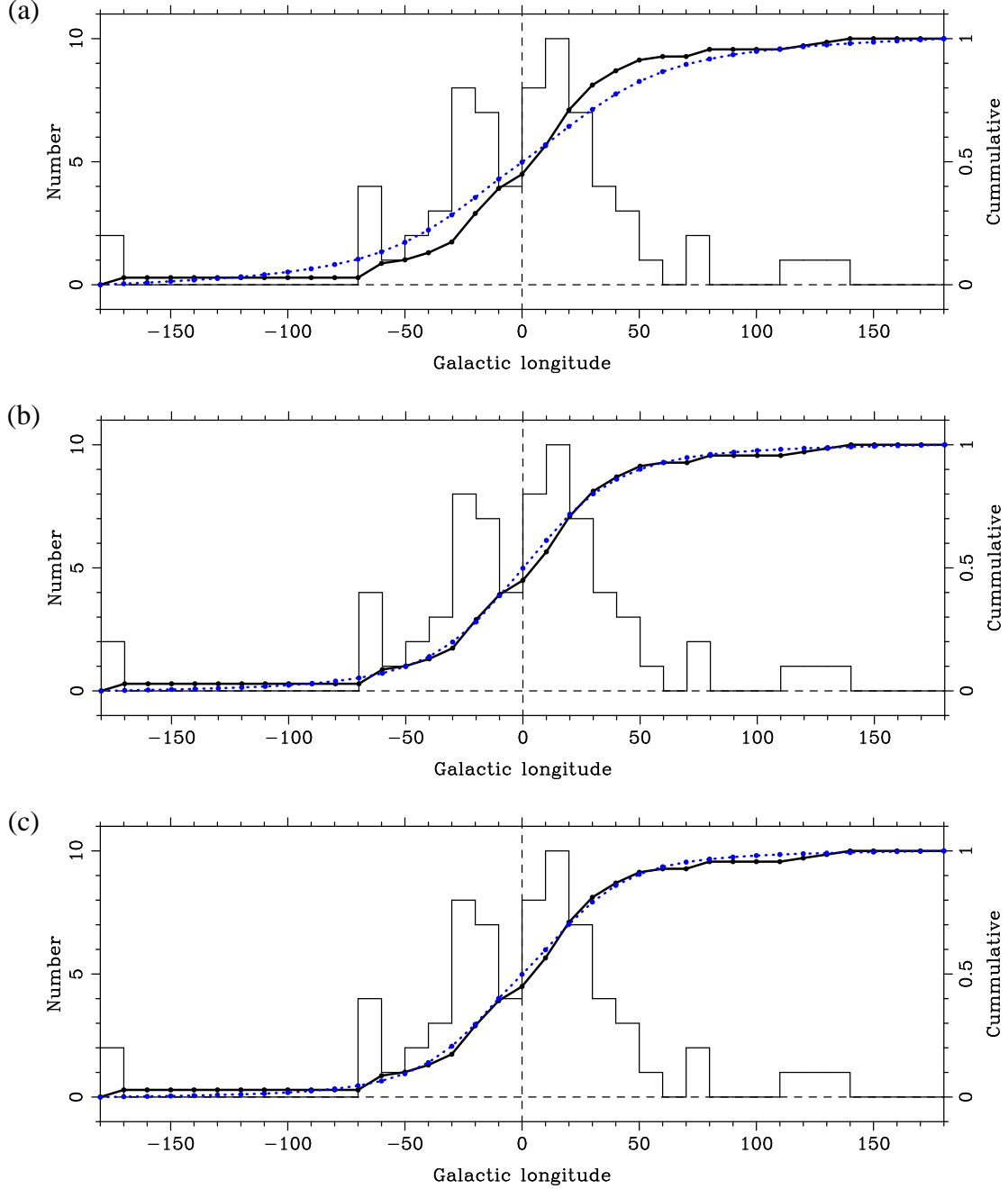


FIGURE 3. Observed l -distribution of bright Galactic SNRs, plotted as histogram (left scale), and cumulative fraction (solid line, right scale), plus cumulative fraction for a model distribution (dotted line, right scale). The three models are for the surface density of SNRs varying with Galactocentric radius, R , as (a) $\propto (R/R_{\odot})^{2.0} \exp[-3.5(R - R_{\odot})/R_{\odot}]$ (as derived by Case & Bhattacharya [1]), (b) $\propto (R/R_{\odot})^{0.8} \exp[-3.5(R - R_{\odot})/R_{\odot}]$, and (c) $\propto (R/R_{\odot})^{2.0} \exp[-5.1(R - R_{\odot})/R_{\odot}]$.

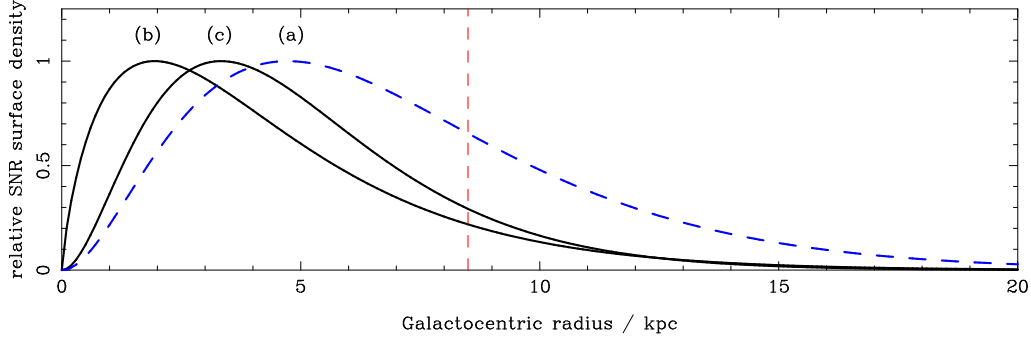


FIGURE 4. Variation of the surface density of SNRs with Galactocentric radius, R , for the power-law/exponential models shown in Figure 3 and discussed in Section : dashed line for Case & Bhattacharya [1]’s distribution (a), and solid lines for models (b) and (c).

projected model distributions for: (a) $A = 2.0$, $B = 3.6$, (b) $A = 0.8$, $B = 3.5$, and (c) $A = 2.0$, $B = 5.1$. The model distribution shown in Figure 3(a), which corresponds to the power-law/exponential distribution obtained by Case & Bhattacharya [1], is clearly broader than the observed distribution of ‘bright’ SNRs above the nominal surface brightness limit of current SNR catalogues (which is to be expected, given the systematic difference due to the regression used by Case & Bhattacharya [1] noted in Section). The model distributions shown in Figure 3(b) and (c) are the best fit – in the sense of minimum sum of least squares of the difference between the observed and model cumulative distributions – power-law/exponential radial distribution varying parameters A and B respectively, but keeping the other parameter as derived by Case & Bhattacharya [1]. Models (b) and (c) have similar least squares differences from the observed cumulative distribution, but correspond to somewhat different distributions in Galactocentric radius, as shown in Figure 4. This shows that there is degeneracy between the parameters A and B in the power-law/exponential distribution model. As discussed above, any residual selection effects that apply to the sample of ‘bright’ SNRs will mean that it is more likely that remnants closer to $l = 0^\circ$ may have been missed. This means that the true distribution may be more concentrated towards $l = 0^\circ$, and hence the distribution will be more concentrated towards smaller Galactocentric radii.

CONCLUSIONS

Observational selection effects, and the lack of distances for many Galactic SNRs means that deriving the Galactic SNR distribution is not straightforward. For a sample of 69 ‘bright’ SNRs – i.e. those not strongly affected by selection effects – the observed l -distribution is shown not to be consistent with the Galactic distribution with Galactocentric radius derived by Case & Bhattacharya [1].

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REFERENCES

1. G. L. Case and D. Bhattacharya, *ApJ* **504**, 761–772 (1998)
2. M. Ackermann et al., *ApJ* **750**, 3 (35pp) (2012)
3. A. E. Vladimirov, G. Jóhannesson, I. V. Moskalenko and T. A. Porter, *ApJ* **752**, 68 (19pp) (2012)
4. D. A. Green, *BASI* **37**, 45–61 (2009)
5. D. A. Green, *PASP* **103**, 209–220 (1991)
6. W. Reich, E. Fürst, P. Reich and K. Reif, *A&AS* **85**, 633–690 (1990)
7. Fürst, E., W. Reich, P. Reich and K. Reif, *A&AS* **85**, 691–803 (1990)
8. W. Reich, E. Fürst, P. Reich and N. Junkes, in *Supernova Remnants and the Interstellar Medium (IAU Colloquium 101)*, eds R. S. Roger and T. L. Landecker, (CUP), 293–296 (1988)
9. D. A. Green, *MmSAI* **76**, 534–541 (2005)
10. T. Isobe, E. D. Feigelson, M. G. Akritas and G. J. Babu, *ApJ* **364**, 104–113 (1990)
11. D. K. Milne, *AuJPh* **32**, 83–92 (1979)
12. T. A. Lozinskaya, *SvAL* **7**, 17–19 (1981)
13. D. A. Green, in *Supernovae and supernova remnants (IAU Colloquium 145)*, eds R. McCray and Z. Wang, (CUP), 341–344 (1996)
14. D. A. Green, *BASI* **32**, 335–370 (2004)
15. L. Bronfman, S. Casassus, J. May and L.-Å. Nyman, *A&A* **358**, 521–534 (2000)
16. D. R. Lorimer et al., *MNRAS* **372**, 777–800 (2006)